Field Testing on Mars: Experience Operating the Pathfinder Microrover at Ares Vallis

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Outline

- Pathfinder and Rover Mission Objectives
- Rover Description
- Surface Operations Scenario
- Command Sequence Generation
- Autonomous Rover Capabilities
- Experiences and Performance on Mars
- The Next Mission

Pathfinder Mission

- Primarily a technology demonstration mission, not a science mission
  - Originally a "pathfinder" for the 16-lander MESUR (Mars Environmental Survey) mission set
  - MESUR cancelled; only Pathfinder remained
- Technologies demonstrated:
  - Low cost entry-descent-landing on Mars (i.e., direct entry, airbags, bouncing, self-righting lander)
  - Rover technologies for future missions (mobility and navigation capabilities in Martian terrain)

Rover Mission Objectives

- Surface Operations
  - Complete one full set of technology experiments (soil mechanics, material adherence, wheel abrasion, etc.)
  - APXS rock data collection
  - Image the lander to assess post-landing condition

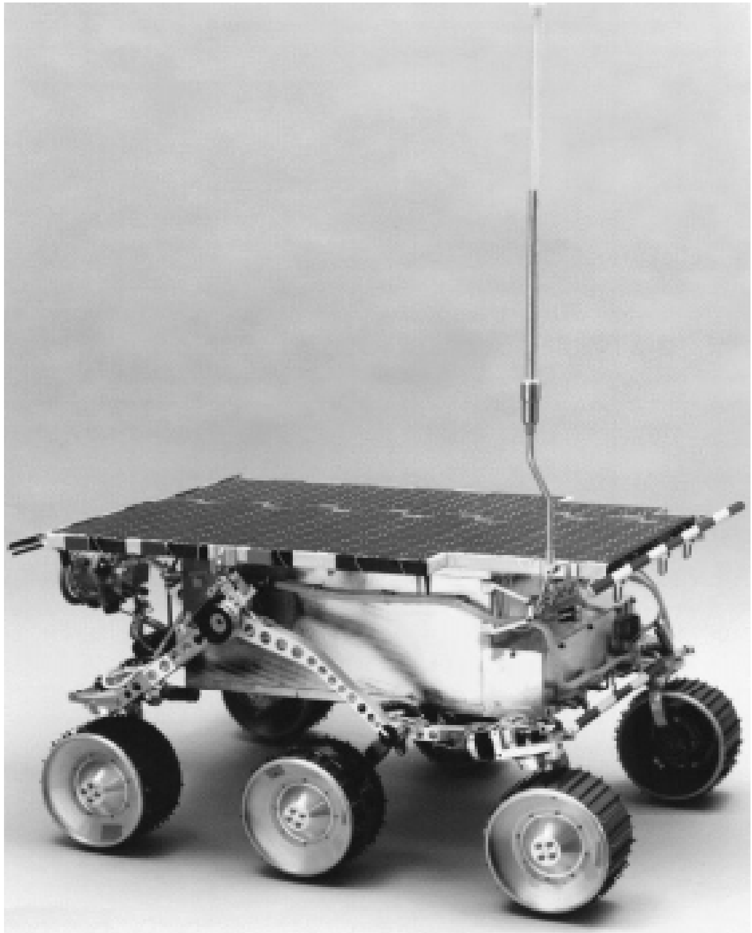
- Prime mission: 7 Sols

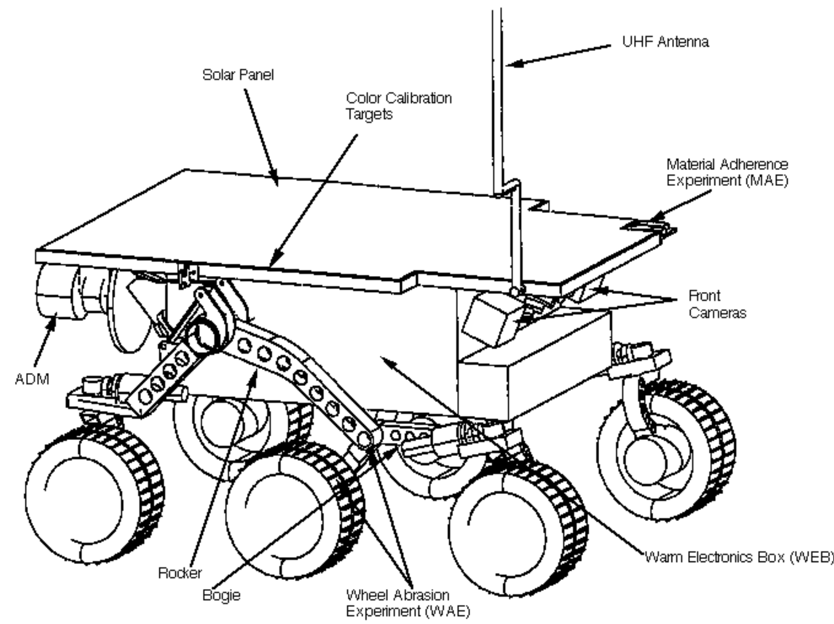
- Extended mission: 30 Sols

- Operating range:
  - Operate primarily within 10 meters of lander
  - Drive up to 100 meters on the Martian surface
  - Be capable of operating beyond the lander’s horizon

Rover Description

- 6-Wheeled robotic vehicle, rocker-bogie mobility chassis
- Mass: 10.5 kilograms
- Deployed volume: 65cm (l) by 48cm (w) by 30cm (h).
- Intel 80C85 CPU (~100Kips), 16K PROM, 64K rad hard RAM, 176K EEPROM, 512K RAM
- Black & White stereo cameras, Color mono camera
- GaAs solar panel (15W peak), Primary batteries
- UHF Radio Modem
- Radioisotope heater units (RHU)
- Laser stripers for hazard detection





Features of the Pathfinder Microrover

Laser stripe for hazard detection as viewed from Sojourner's left front camera on sol 8

Constraints Driving Rover Operations Scenario

- Earth-Mars communications time delay (approximately 20 minutes round-trip on landing day)
- Limited communications bandwidth (generally < 10 Mbits downlink per sol available to rover)
- Limited communications opportunities (1 command uplink, 2 telemetry downlinks per sol)
- No repairman within 100 million miles

Surface Operations Scenario

- Rover operations team prepares one command sequence each Martian sol
- Rover nominally operates autonomously for one sol (>24 hours) until receipt of next command sequence. Activities include imaging, traverse, technology experiments, APXS sensor placement & instrument operation (day/night)
- Lander camera captures stereo image of rover at its end-of-day location
- Downlinked images and rover telemetry used by rover team to assess rover state and plan next sol's activities

Command Sequence Generation

Rover Control Workstation (RCW)

- 3D Stereoscopic interface
    - Computer Aided Remote Driving
    - Rover localization and position update
    - Virtual Flying Camera
- Sequence Planning
    - GUI interfaces for complete command dictionary
    - Output generation, insertion into uplink load for spacecraft
- Facilitates rapid command turnaround
    - Only a few hours from receipt of telemetry to sequence generation, unlike previous missions

Autonomous Rover Capabilities

- Natural terrain traverse
  - Operator designates intermediate and final waypoints to avoid visible hazards
  - Rover deviates from nominal path in response to local hazard detection
  - Onboard sensing includes tilt, acceleration, laser stripers, gyroscope, wheel odometry, contact
  - Find rock and “thread-the-needle” capabilities

- Contingency response
  - Earth/Lander command loss: Backup mission load
  - Lander/Rover command loss: Contingency mission

Lessons of Sojourner

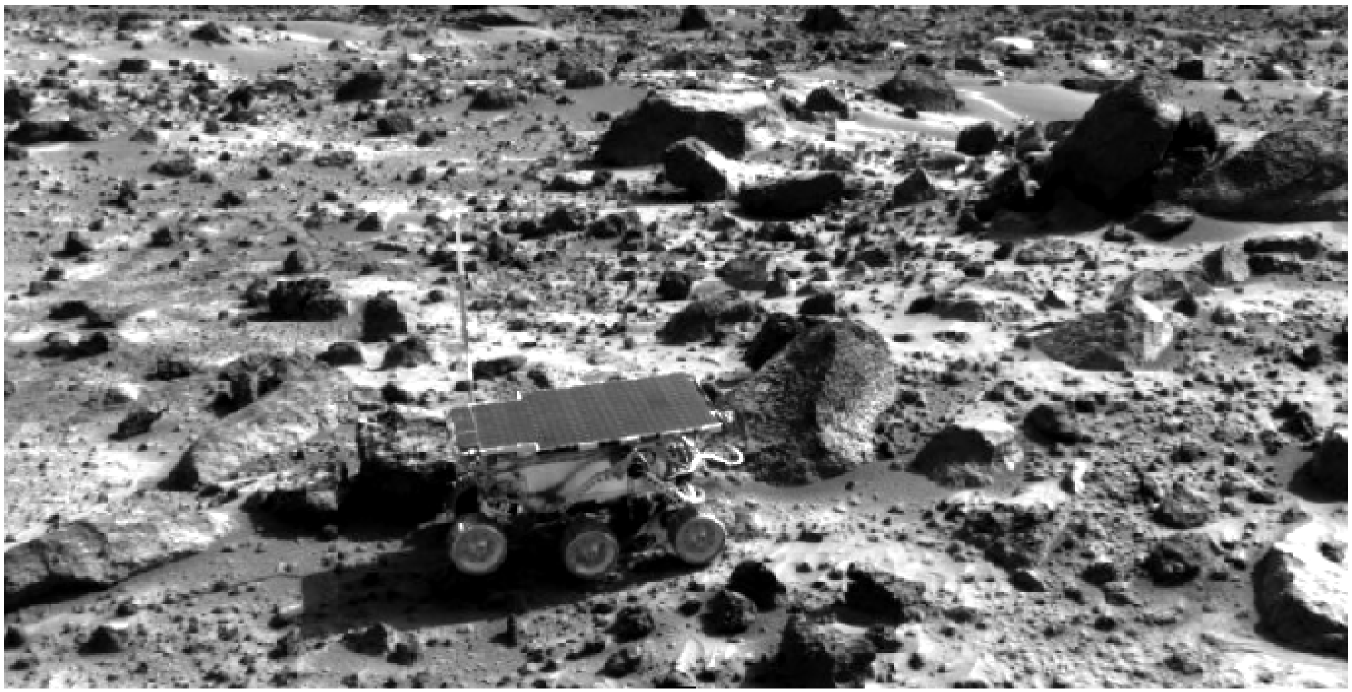
- Make sure you have a small enough team to do the job
- There is never enough time to complete integration and test
- Schedule/resources may not permit correction of problems identified during development
- What isn't fixed in hardware is fixed in software. What isn't fixed in software is fixed in operations.

Testing on Earth

- Desire:
  - Develop experience base operating rover equivalent to multiple prime missions

- Reality:
  - Schedule and resource constraints severely limited number and kinds of field tests
  - Operations readiness tests with project largely limited to rover unstow and egress
  - Most of operations team not available until after launch
  - Approximately 20 multi-sol "sandbox" tests performed during 7-month cruise; with cross-training each team member had ~five opportunities to learn each of his/her roles.

Field Testing on Mars



**Sojourner to the left of the rock "Wedge" on Sol 35.
Part of the "Rock Garden" is visible in the upper right of the image.**

Field Testing on Mars

- Overall Observations:
  - Rover operations went more smoothly on Mars than during Earth testing
    - Only attempted one uplink per Earth day
    - Infrastructure in place to support continuing operations
  - Incremental costs (in terms of schedule and personnel) made extensive testing of rover technological capability more feasible on Mars than on Earth (long range autonomous traverses were about to begin when lander communications was lost on sol 83)

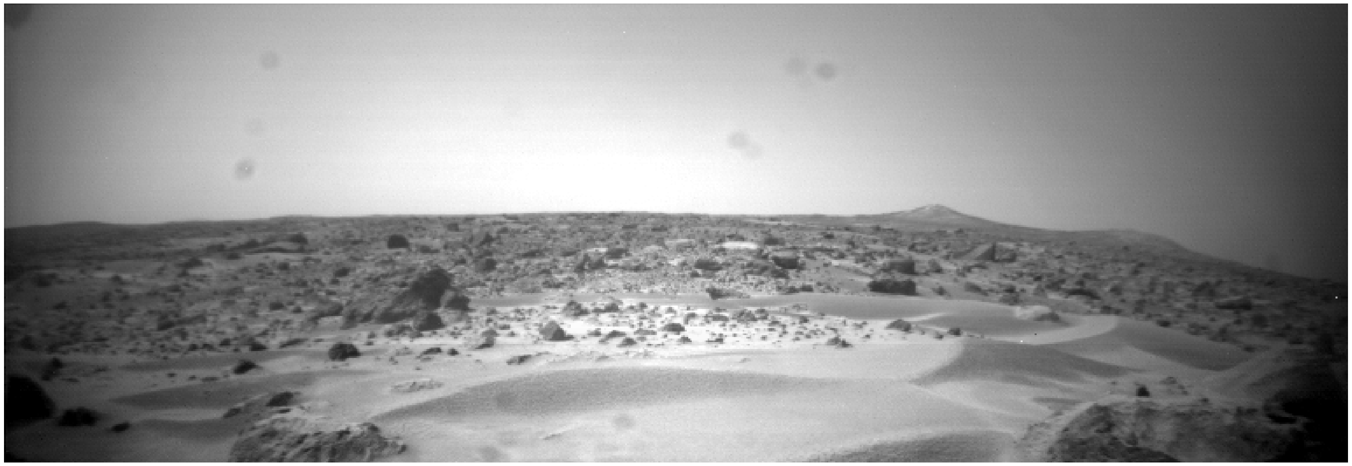
Field Testing on Mars (cont.)

- Ground truth difficult to come by:
  - Limited tracking of rover position during traverse by lander camera
    - rover “movies”
    - “End-of-sol” pictures
  - Analysis of rover track images (when available) enabled further reconstruction of rover path

Performance On Mars

- Prime mission goals achieved in first week
- Imaged sites beyond lander's visual horizon
- APXS spectra collected for 16 sites (9 rocks, 7 soil locations)
- Over 100 meters integrated traverse distance
- Over 500 images captured
- Rover still operating on sol 83 when communications with lander was lost

Closeup rover image of the rock “Chimp”



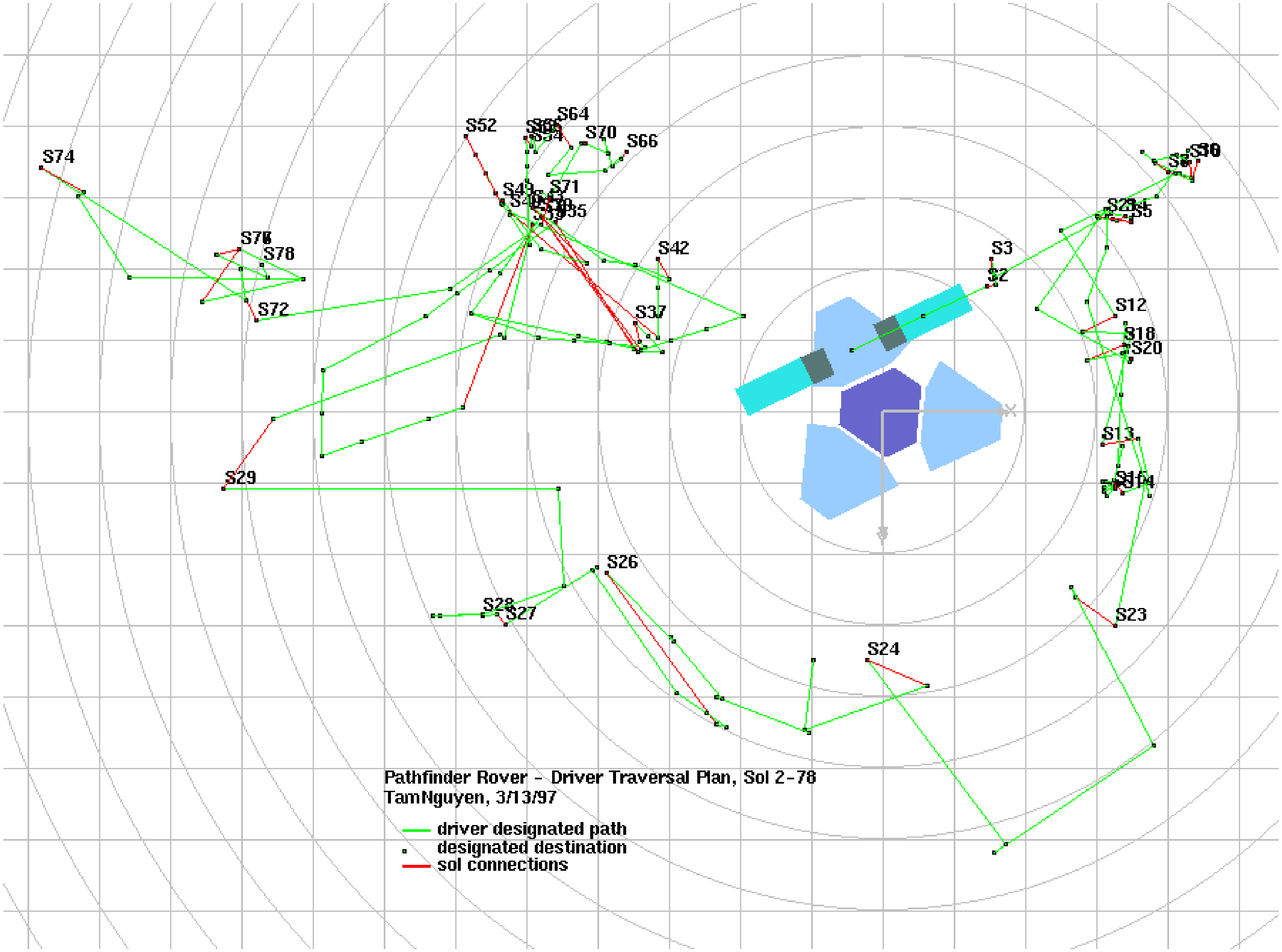
Dunes behind the “Rock Garden”
visible only from the rover

Problems Encountered during Mars Operations

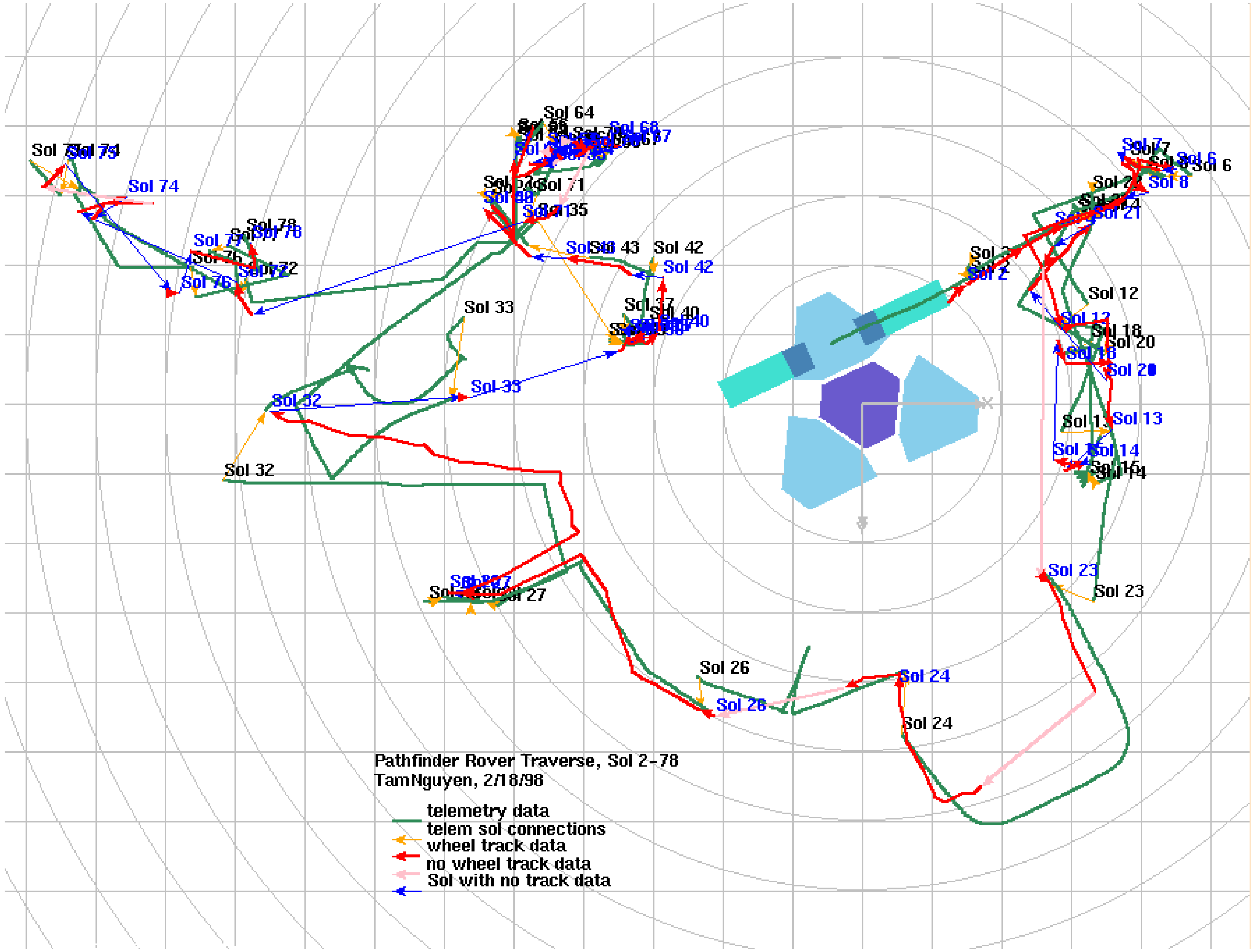
- Poor rover-lander communications
- Intermittent accelerometer failures
- Significant gyro drift
- Lack of a true onboard rover mission clock
- Premature loss of primary battery
- Failure of single external motor temperature sensor
- Poor color camera performance
- Problems caused by our own success:
  - Operations team fatigue
  - Unexpected failure modes in solar-only mode
  - Increasing interest in close-up imagery and additional experiments led to oversized sequences
  - Limited DSN availability later in mission made many sols effectively very short

Strategies Adopted to Improve Mars Operations

- Heated RF modem to minimize frequency drift
- Selectively enabled accelerometers depending on terrain
- Eventually chose to rely on wheel encoders to measure turns instead of gyro
- Used sensor-based conditionals to minimize battery use for APXS
- Relied more heavily on forward B&W cameras for science imaging



Operator Designated Traverse Plan: Sols 2 to 78



Sojourner Traverse: Rover Estimate and Ground Truth

The Next Mars Field Test: Mars Surveyor 2001 Rover Mission

- Survive up to one Earth year on the surface
- Free-ranging rover (no lander support)
- Communicate direct to orbiter (~2 five minute passes per sol)
- Traverse multiple kilometers
- Cover up to 100 meters per sol
- Incorporate sophisticated suite of science instruments
- Core drill and cache rocks and soil for future return mission
- Increase autonomy to support mission requirements
- Must be able to sustain operations with small team

Acknowledgements

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- The rover path reconstructions and graphs showing operator-designated traverse plans and rover-estimated paths were provided by Tam Nguyen of the JPL Mars Pathfinder rover team.